Power and Particle Exhaust for Infinity Two Fusion Power Plant

IAEA – Fifth Technical Meeting on Divertor Concepts, Vienna, Austria

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Our Team: Type One Energy Physics Group

D. T. Anderson[1], E. C. Andrew[1], A. Bader[1], A.De[1] , T. D. Bohm[2], K. Camacho Mata[1], J. M. Canik[1], L. Carbajal[1], A. Cerfon[1], D. W. S. Clark[1], W. A. Cooper[3], N. M. Davila[1], J. M. Duff[1], H. Frerichs[2], B. Goh[1], W. Guttenfelder[1], C. C. Hegna[1], C. Holland[1], D. P. Huet[1], J. Kessing[1], M. Knilans[1], M. Landreman[1], C. Lau[1], G. Le Bars[1], A. Malkus[1], N. R. Mandell[1], B. Medasani[1], C. Moreno[2], J. Morrissey[1], T. S. Pedersen[1], E. Pflug[2], S. Ramirez[1], J. Smandych[2], J. C. Schmitt[1], P. Sinha[1], L. Singh[1], Y. Suzuki[4], M. S. Tillack[1], J. Varela Rodriguez[1], K. Willis[1] and P. P. H. Wilson[2]

Thanks to D. Garcia and J. Talley (Divertor Engg. Team)

[1]Type One Energy Group, Inc

[2]Department of Nuclear Engineering, University of Wisconsin-Madison

[3]Swiss Alps Fusion Energy (SAFE), Vers l'Eglise, Switzerland

[4]Graduate School of Advanced Science and Engineering, Hirshoshima University

* T1E **Divertor Physics Group** in **GREEN**

Contents

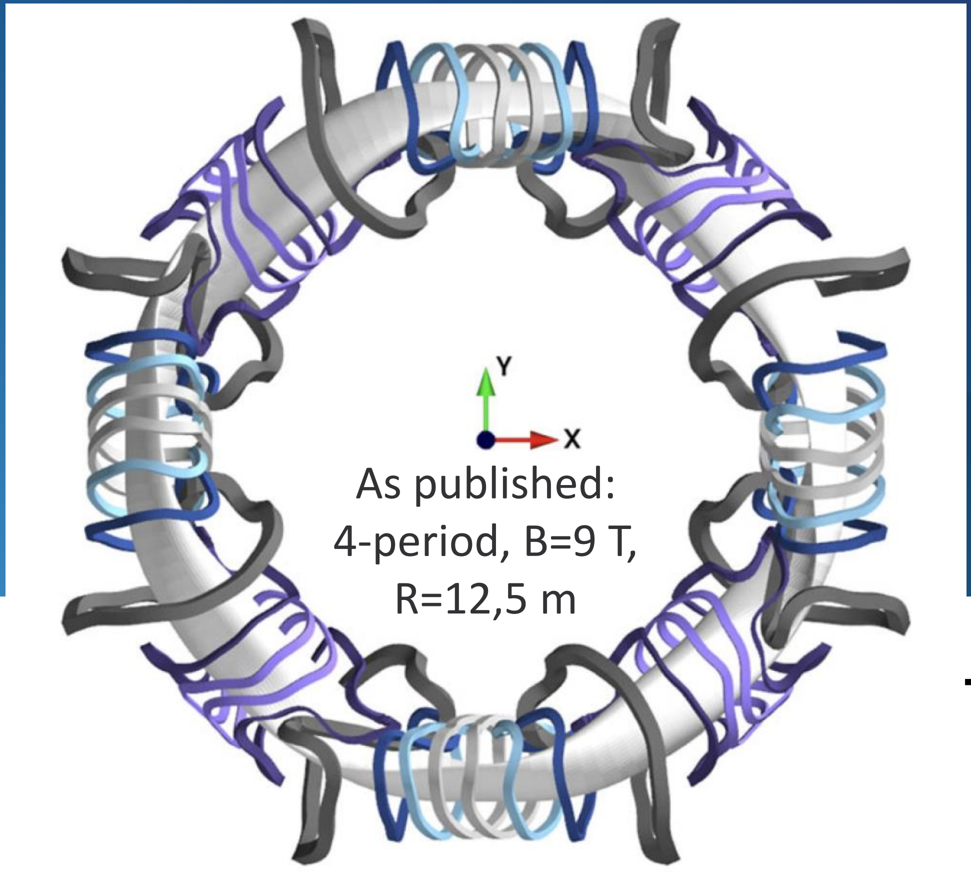
A direct path to contracting the first Fusion Power Plant project before 2030

Enablers Ready	Program Launch	1st De-risking Milestones	2nd De-risking Milestones	Design Complete and Verified	FPP Deployment
2018	**2023**	**2025**	**2027**	**2028**	**2029-2035**

Fusion Power Plant development and design
Project Infinity: validate FPP design by test on integrated prototype (Infinity One)

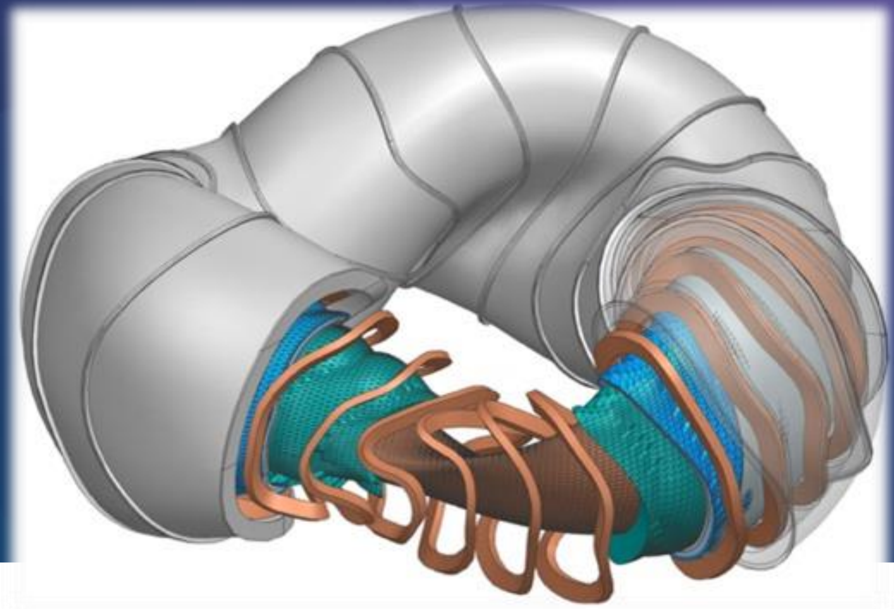
Infinity One Operation

Infinity Two Physics Basis



As published:
4-period, B=9 T,
R=12,5 m

→ Six months later →



New configuration:
3-period, B=8 T, R=11.4 m
Meets or exceeds all metrics of
the published configuration

" Physics Basis of the Infinity Two Fusion Power Plant", Journal of Plasma Physics, v. 91 Issue 3 (2025)
Six scientific papers and one editorial paper, peer reviewed and open-access on JPP website

Infinity Two Divertor Requirements for Good Plasma Performance

- **Divertor heat and particle fluxes**: reduced enough to maintain divertor integrity
  - → Below engineering and sputtering limit (q_{max}<5 MW/m^2)
  - → W7-X could demonstrate stable plasmas at high radiative fraction and low target heat flux
- **Neutral pressure in the divertor**: exhaust of main species and impurity particles – plenum pressure ~ 1 Pa
  - → Achieving good W7-X particle exhaust was a challenge
- **Neutral compression**: ratio of downstream neutral pressures to upstream values: ratio as high as possible
- **Radiative fraction**: ratio of radiated power to input power: high with most being located at island SOL
  - → understand detachment physics and stability
- **Core plasma parameters**: core plasma should be stable during detachment; performance maintained

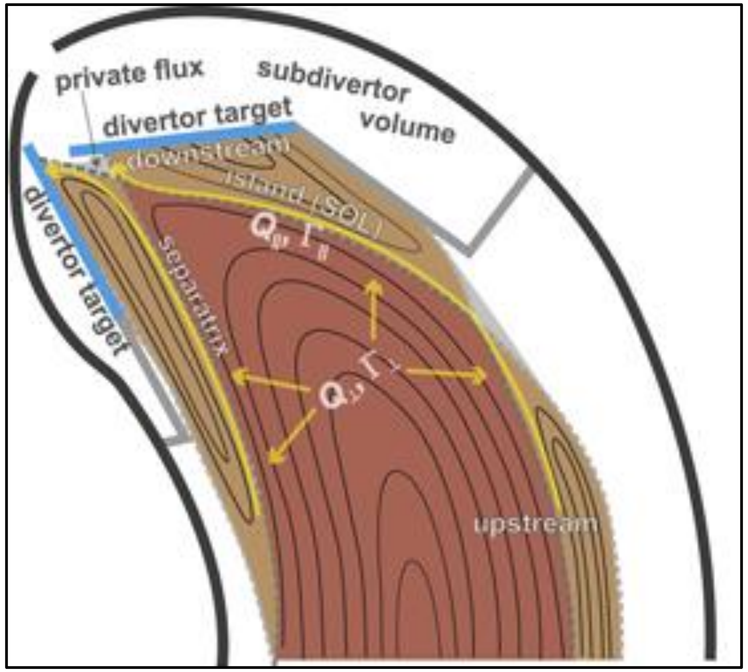
Understanding Island Divertor Physics

Island divertors selected for power and particle exhaust

- W7-AS and W7-X : wealth of data and knowledge available

	X-point Poloidal Divertors	Island Divertors
Rotational Transform (ι)	$\iota = \frac{n}{m}$	$\iota_{total} = \frac{n}{m} + \iota_i$ $\iota_i = r_i s$
Field line pitch (Θ)	$\Theta = \iota a/R \approx 0.1$	$\Theta = \iota_i a/R \approx 0.001$
Connection lengths (L_c)	$L_c \approx \frac{2\pi R}{N\iota}$ (tens of meters)	$L_c \approx \frac{2\pi R}{N\iota_i}$ (hundreds of meters)

- Role of perpendicular transport in IDs much larger than tokamaks → sets the target scrape-off layer width (λ_{qt})
- Understanding sensitivity of λ_{qt} on χ, D, L_c and other important factors like magnetic field



Field lines inside the island intersect divertor target plates

Ref: Jakubowski, M., et al. *Nuclear Fusion* 61.10 (2021): 106003. DOI: 10.1088/1741-4326/ac1b68.

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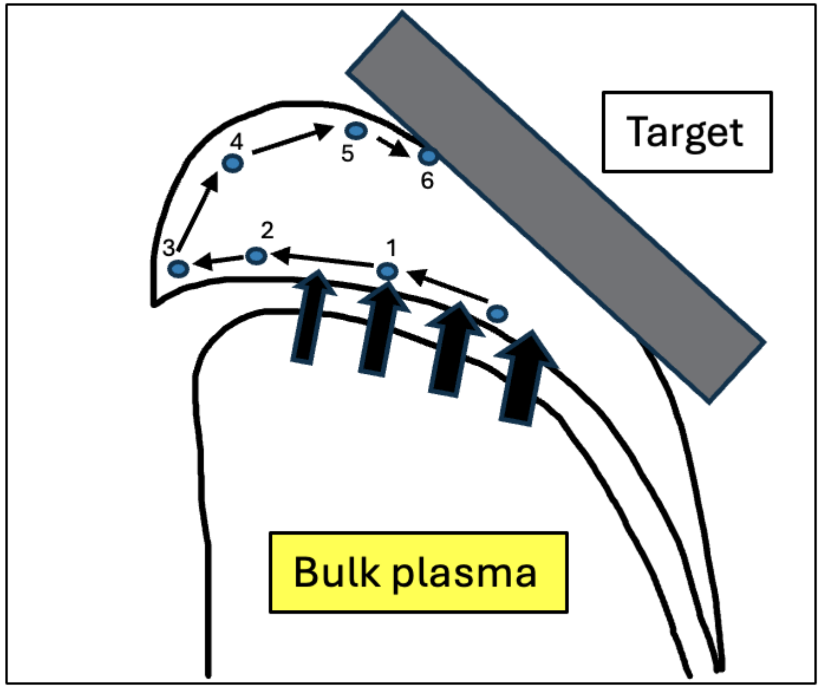


Cartoon of field lines inside the island intersect divertor target plates

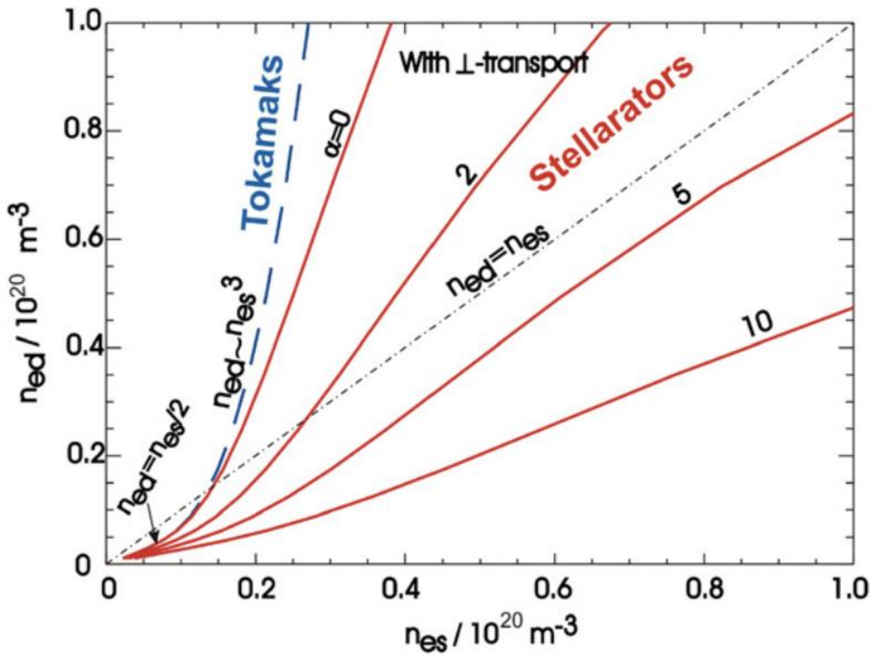
Scrape-off Layer (SOL) features that differentiates stellarators with tokamaks

- Momentum loss in stellarators : Counterflows residing on neighboring island fans

$$p_u = 2pd(1 + fm) \quad \text{where } f_m = \alpha/Td^{0.5}$$

- Downstream density lower than the upstream density
  → Neutral pumping a challenge in IDs

- In stellarators, large part of the SOL periphery facing the wall lies 'downstream' and protects the wall from direct exposure to the hot 'upstream' plasma
  → Better impurity retention in IDs



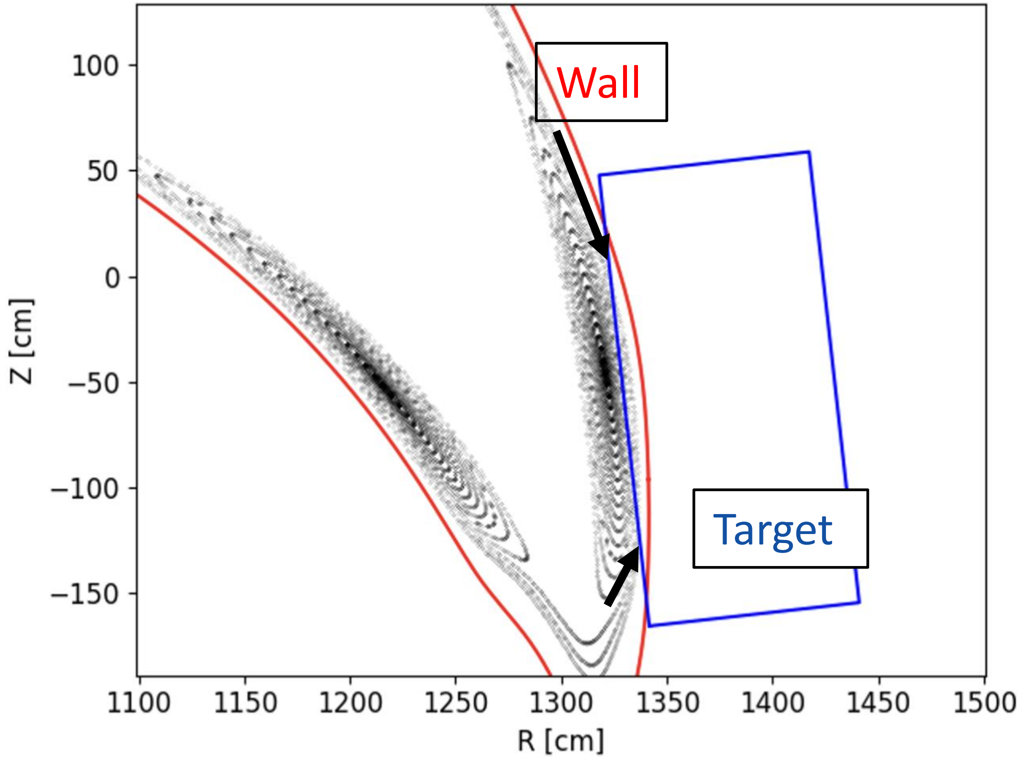
Comparison of divertor transport behaviour in W7-AS, W7-X and ASDEX Upgrade calculated by EMC3-EIRENE.

Ref: Feng, Y., et al. PPCF 53.2 (2011): 02400. DOI: 10.1088/0741-3335/53/2/

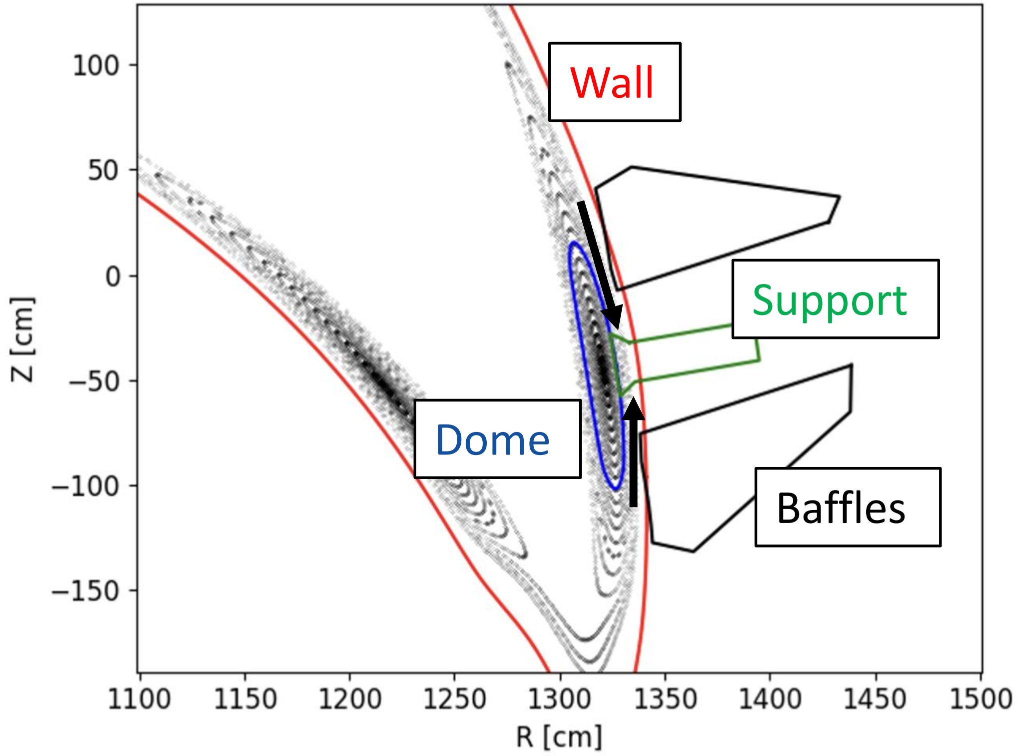
Different Divertor Concepts Explored for Particle and Power Exhaust

Exploring Open and Closed Divertor Concepts for Exhaust (in 2D)

Classical Divertor

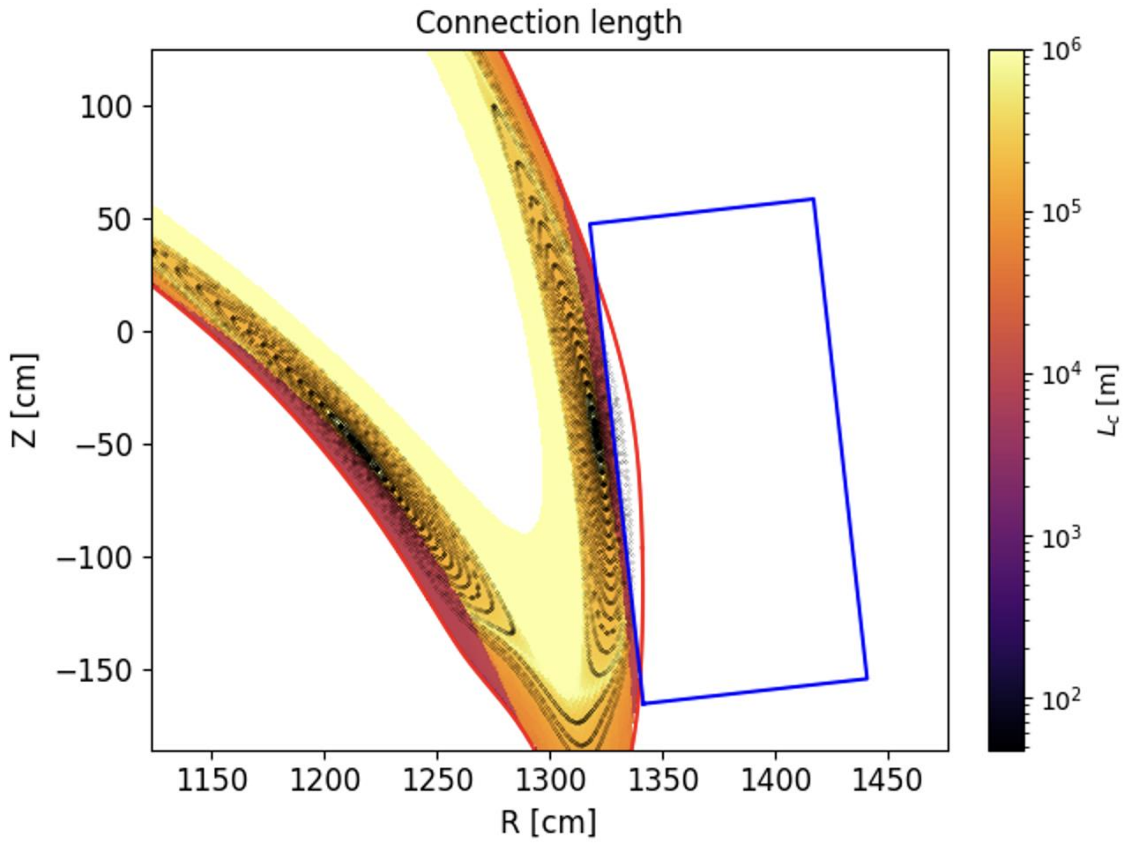


Backside Divertor



Exploring Open and Closed Divertor Concepts for Exhaust (in 2D with Connection lengths plot)

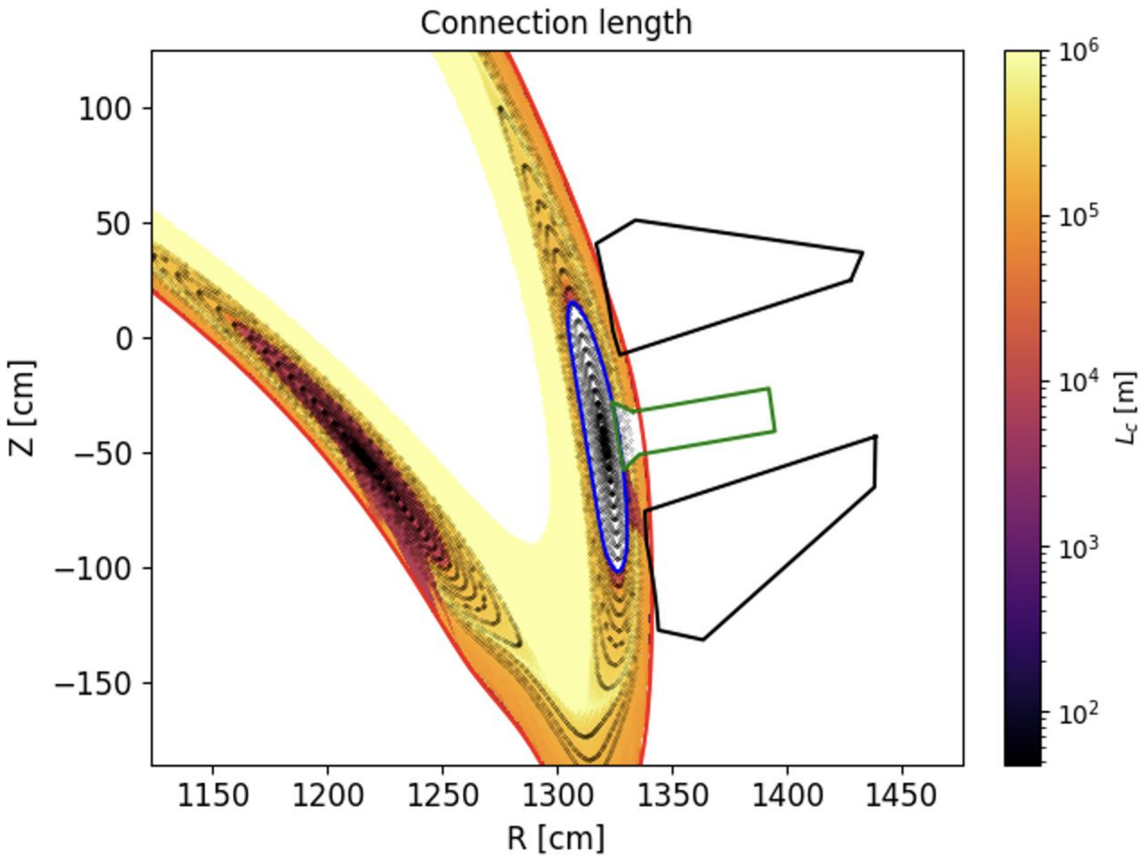
Classical Divertor



- Design is similar to W7-X divertor
- **Targets** inclined at 3 deg to the magnetic field
- Neutral pumping could be challenging due to inefficient neutral retention
- Optimization of target shape ongoing for better heat load distribution and pumping

Exploring Open and Closed Divertor Concepts for Exhaust (in 2D with Connection lengths plot)

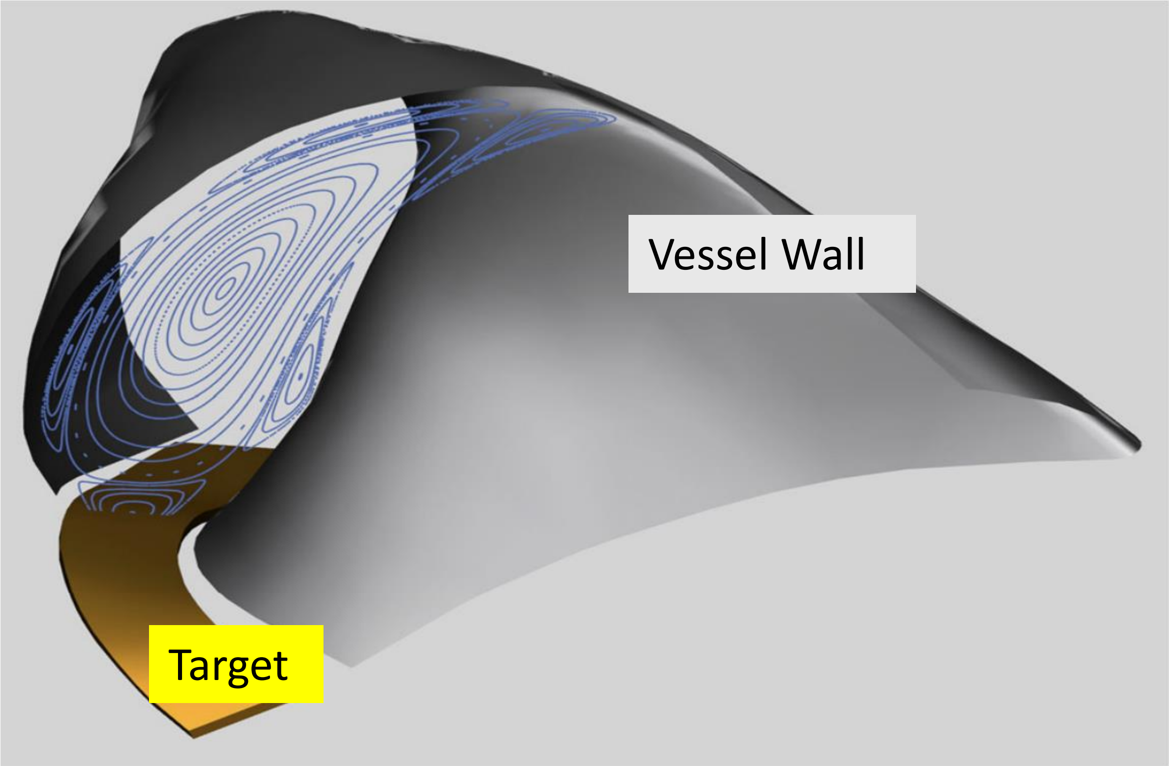
Backside Divertor



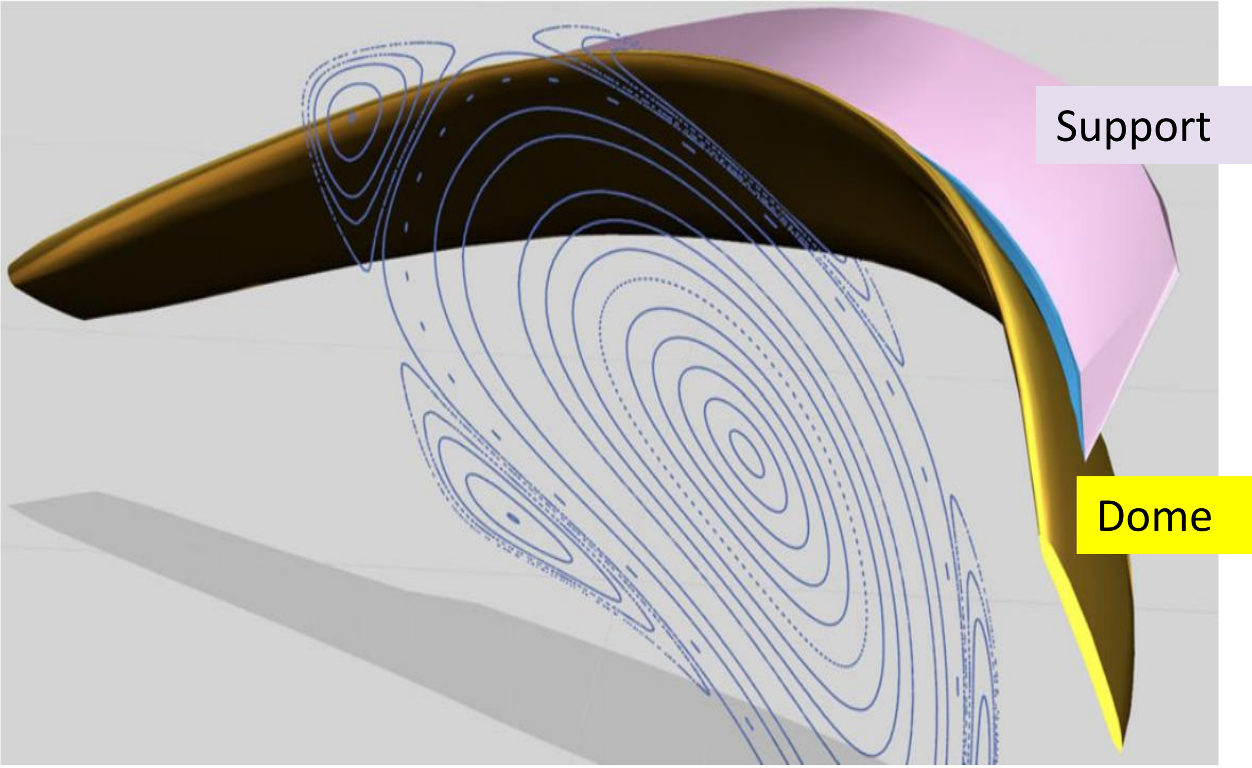
- Promises improved neutral pumping
- Closing the divertor using **baffles** and with a structure inside the island (**dome**)
- Prevents neutralized plasma particles from re-entering the plasma

Exploring Open and Closed Divertor Concepts for Exhaust (in 3D)

Classical Divertor



Backside Divertor



Analysis tools used for Heat and Particle load estimation

General workflow: Reduced fidelity model for divertors optimization and high-fidelity model for in-depth divertor physics analysis

Coils and MHD team provides equilibrium →

FLARE

If heat-load distribution good enough →

EMC3- EIRENE

Divertor design shared with Engg. team →

FLARE

- Low-fidelity
- Needs less computational resources
- Very quick used for initial tweaking/optimization of divertor geometry
- Diffusion model used for heat and particle load estimates

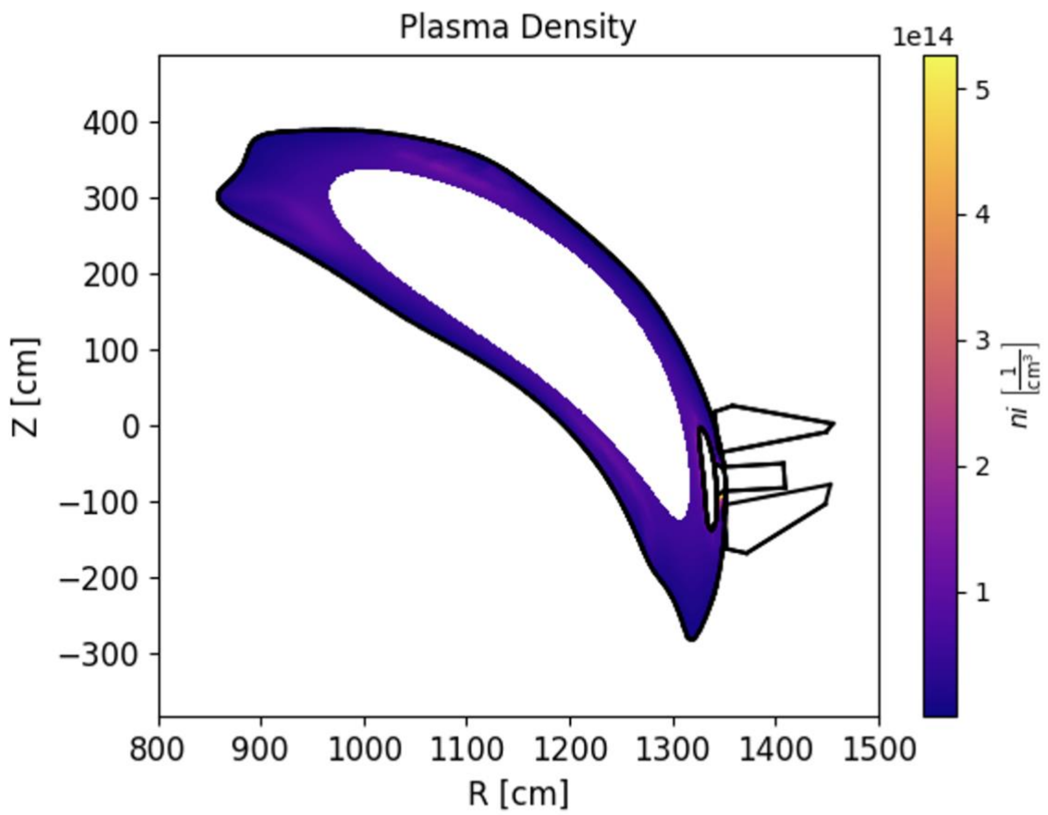
EMC3- EIRENE

- High-fidelity
- Large computational resources required
- Monte-Carlo fluid model for steady state plasma coupled with kinetic model for neutrals
- Provides data on density, temperature, target heat and particle loads, neutral pumping etc.

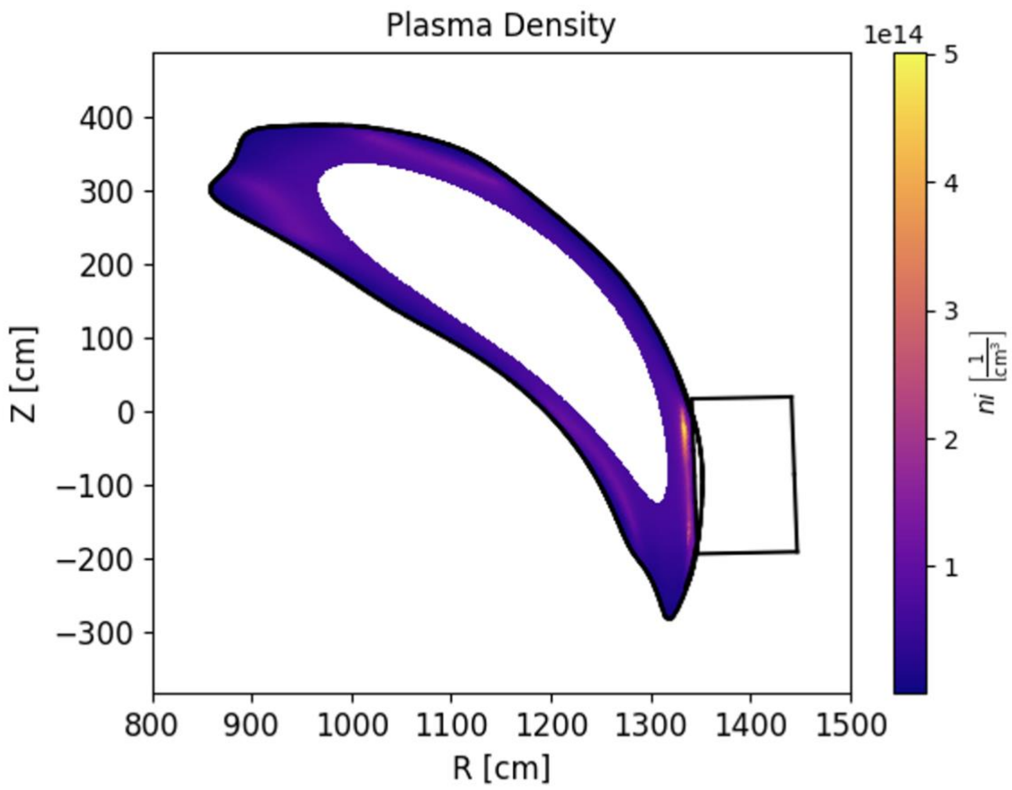
Analysis of Divertor SOL properties for Infinity Two

Plasma density comparison using EMC3-EIRENE for both divertor concepts

- EMC3- EIRENE calculations performed with n_{IBS} = 7* 10^{13} cm^{-3}, χ = 3 m^2/s, P_{SOL} = 100 MW and no impurities

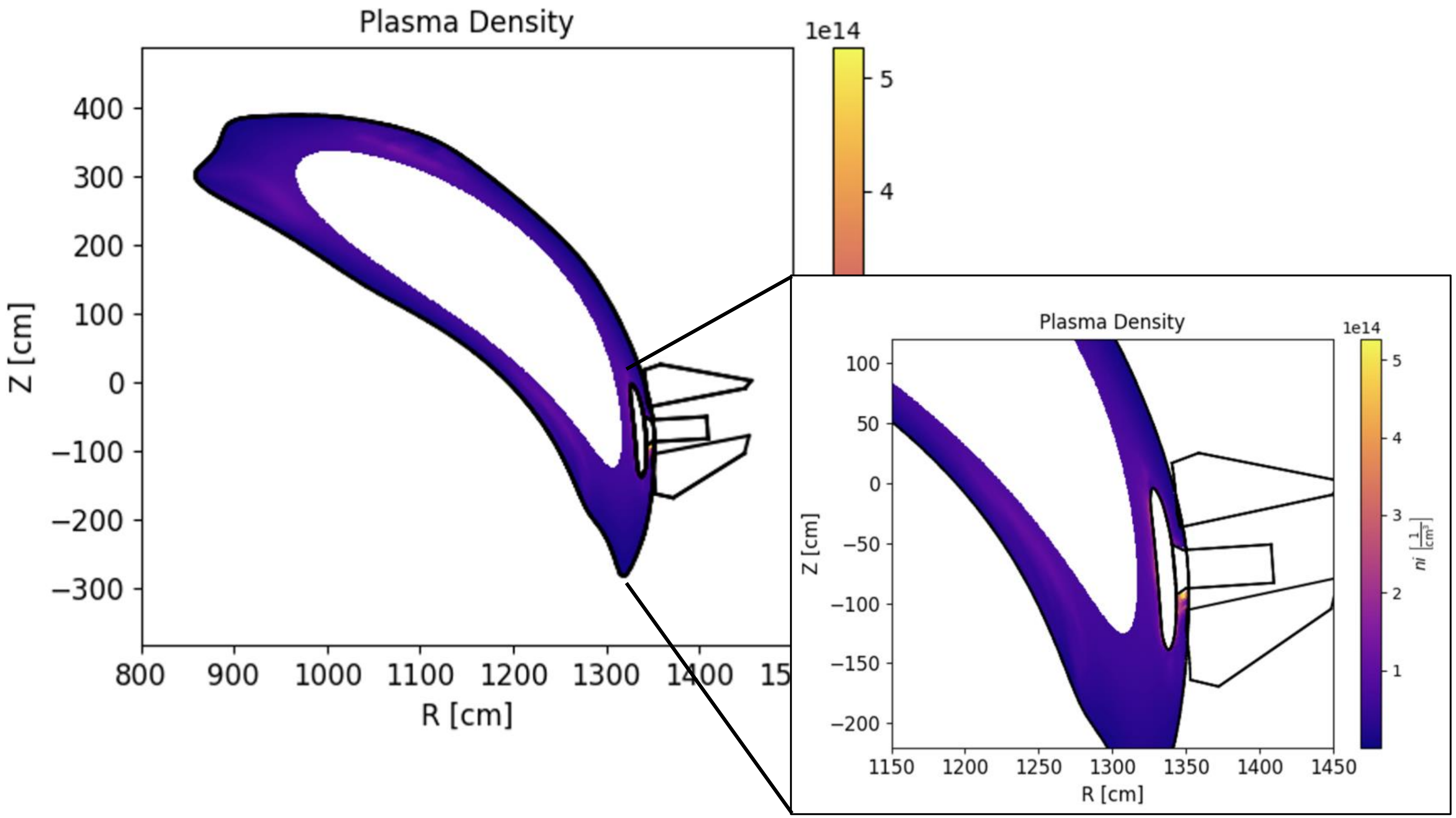


Backside Divertor



Classical Divertor

EMC3-EIRENE results show plasma build up on the backside of the dome

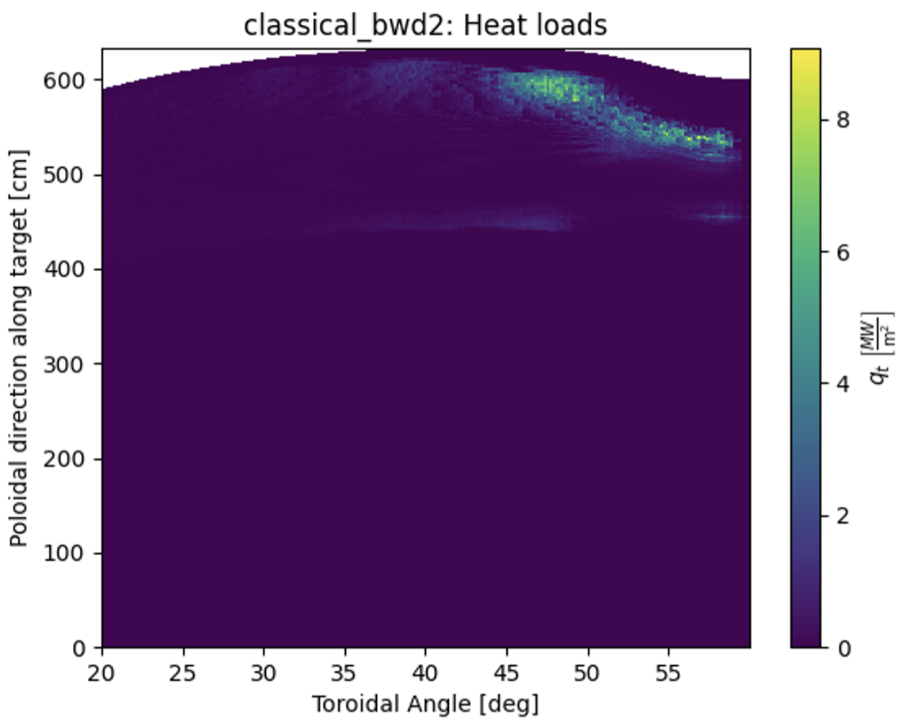


- Build-up in right place → likely to increase the plenum pressure
- Radiation front will move as f_{rad} increases
- Study in progress to understand the effect of the shift of radiation front with increase f_{rad}

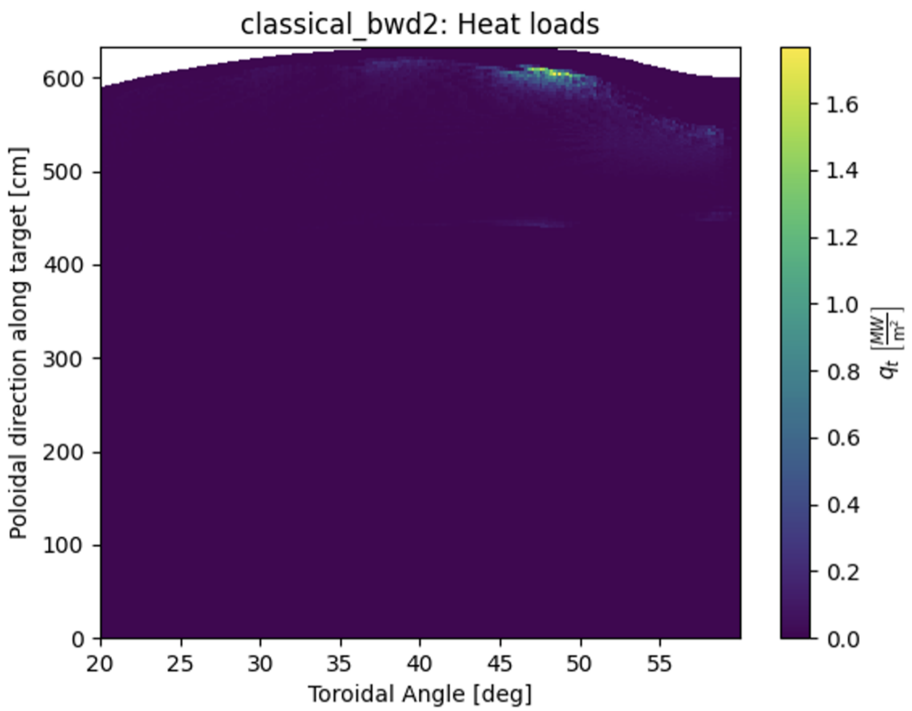
Peak heat flux on the divertor plate decreases as the f_{rad} increase (in 2D)

<u>Classical Divertor</u>

- EMC3- EIRENE calculations performed with $n_{IBS} = 7 * 10^{13}$ cm^{-3}, $\chi = 1.5$ m^2/s, $P_{SOL} = 100$ MW

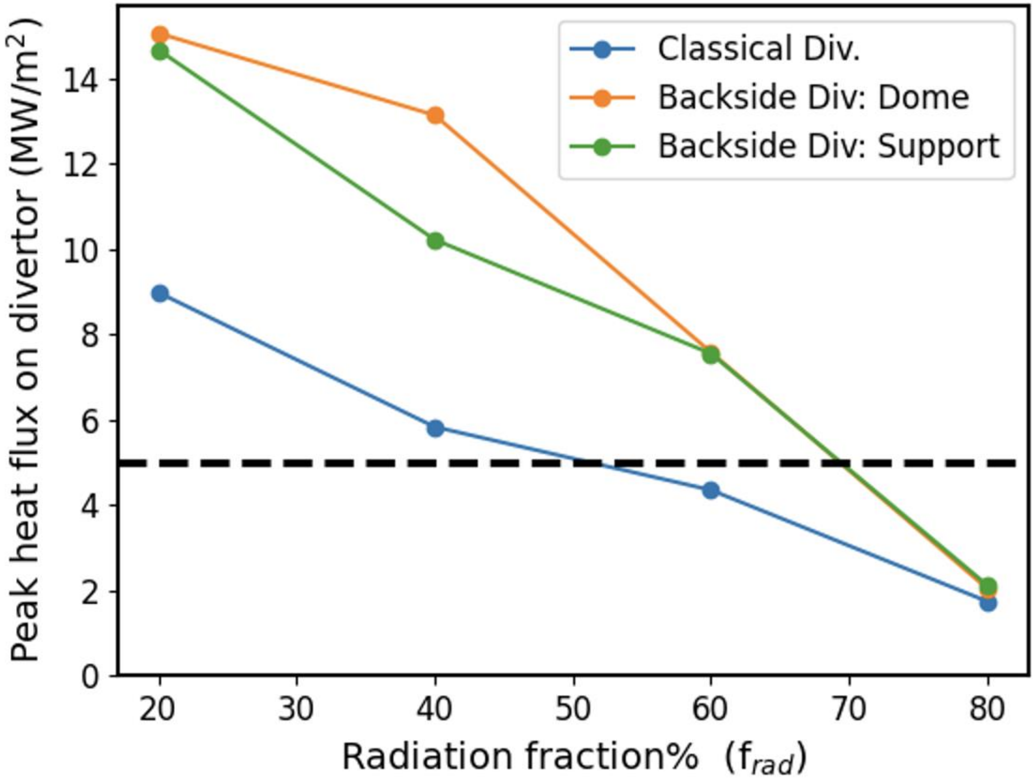


Heat load on divertor plate with 20% f_{rad}



Heat load on divertor plate with 80% f_{rad}

Peak heat load decreases as f_{rad} increases for both divertor concepts



Lehmer Peak Heat Flux

$$L(x) = \frac{\int q^{30}\, ds}{\int q^{29} ds}$$

Where q = Heat load in MW/m^2

s = entire surface area of the relevant target

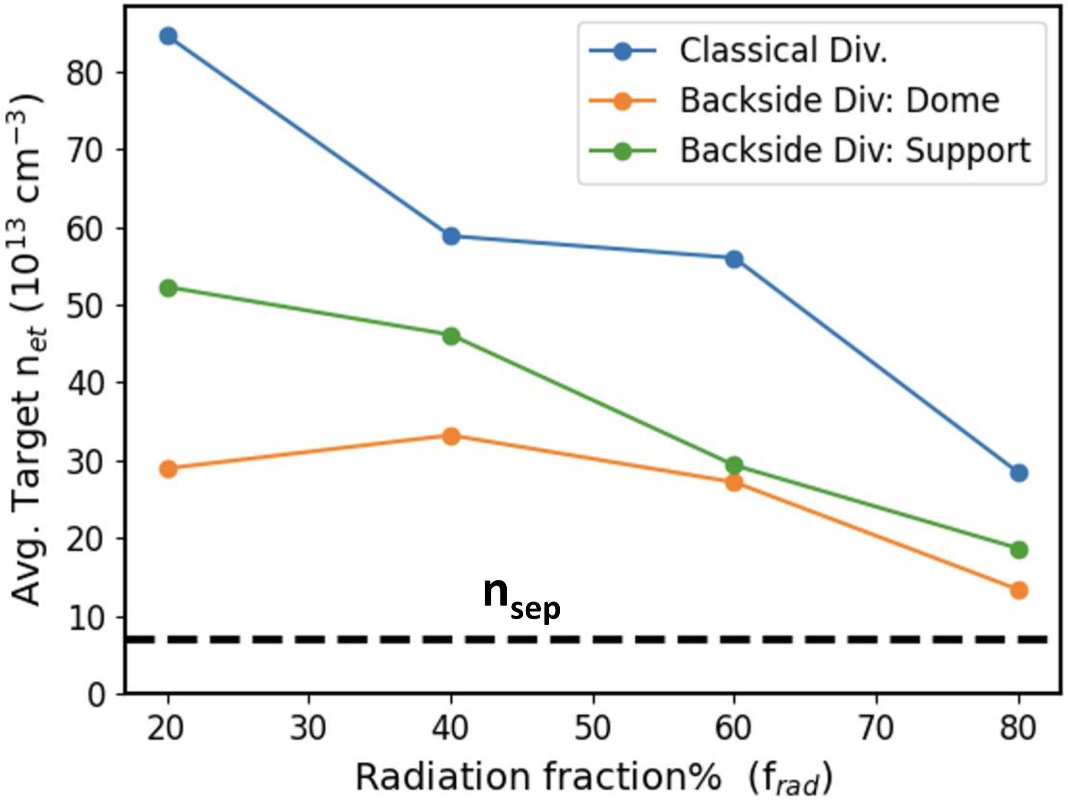
P_{alpha}+P_{ech}>=160 MW, P_{SOL}=100 MW

$P_{rad,core}$=60 MW, $f_{rad,core}$~40%, f_{Ne}=0.5%

→ $f_{rad,SOL}$ =50-70% → $f_{rad,tot}$ = 68-81% requirements

Ref: Guttenfelder, W., et al. JPP 91.3 (2025): E83

Flux averaged target density decreases as f_{rad} increases for both divertor concepts



<u>Flux Average Target Density</u>

$$n_t = \frac{\int n\,\Gamma_s ds}{\int \Gamma_s ds}$$

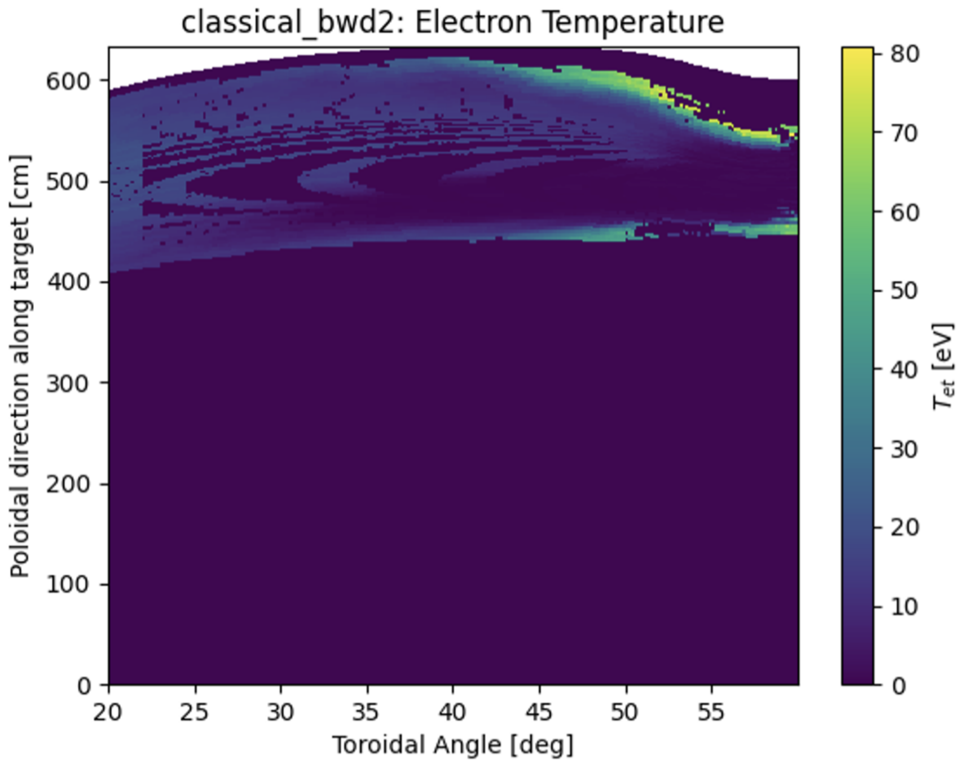
Where x = Target density. in 10^{13} cm^{-3}

s = entire surface area of the relevant target

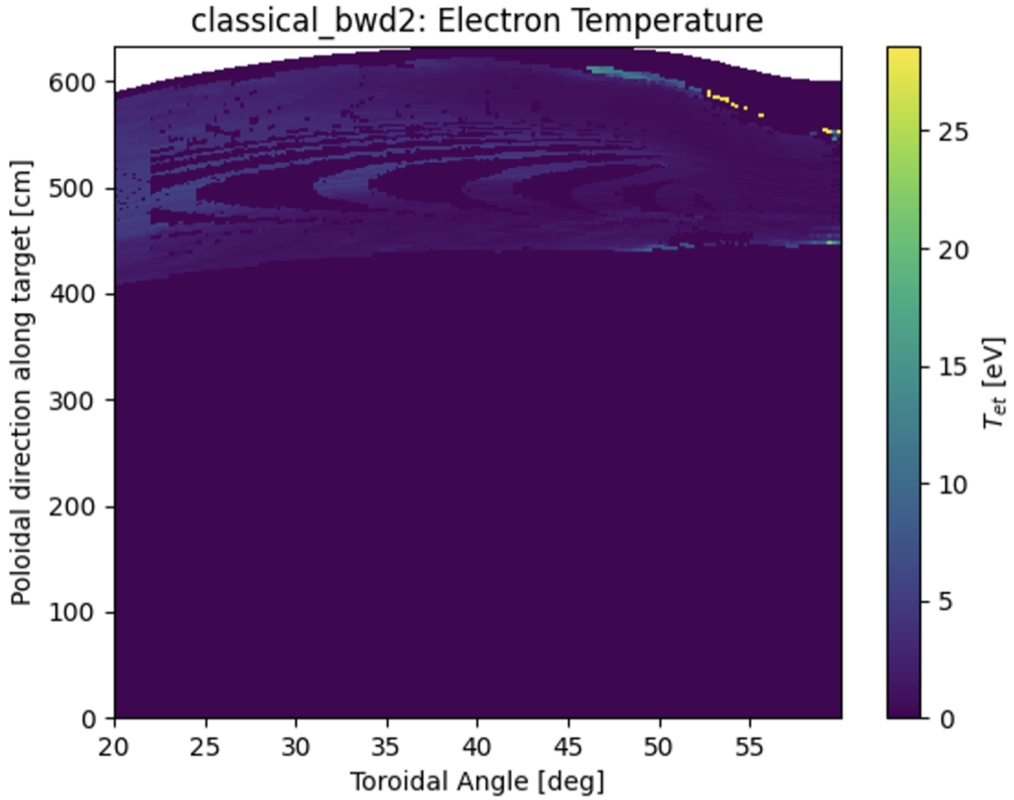
Γ_s= particle flux at the surface element ds

Peak target temperature on the divertor plate decreases as the f_{rad} increase (in 2D)

Classical Divertor

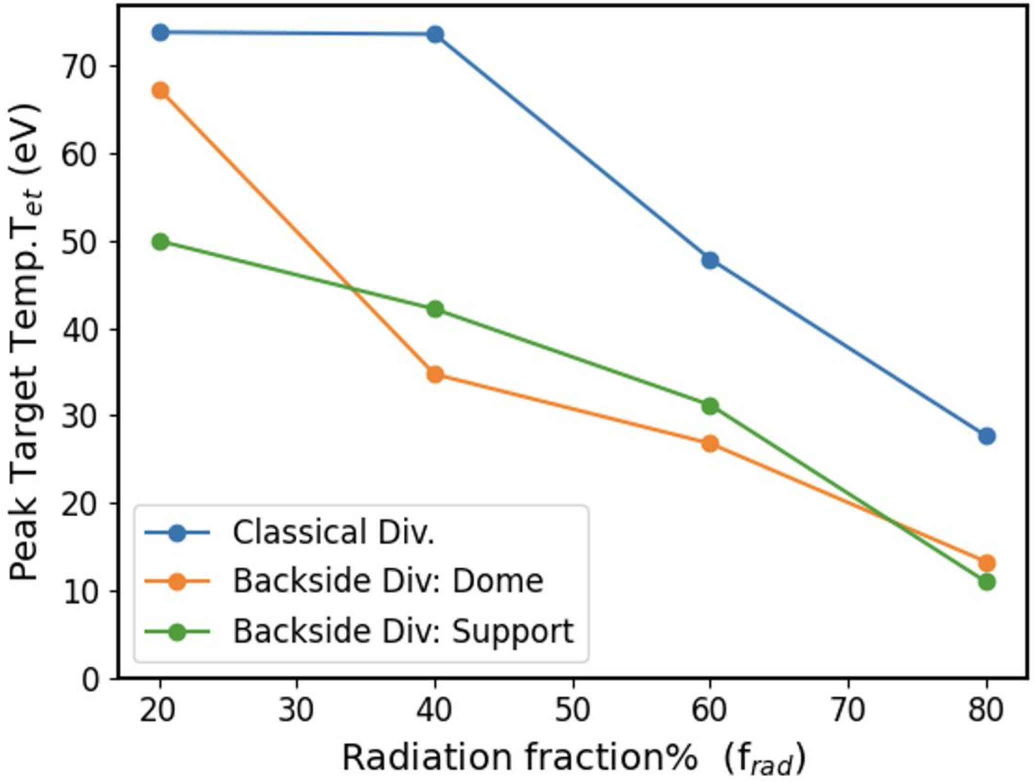


Electron Temp. on divertor plate with 20% f_{rad}



Electron Temp on divertor plate with 80% f_{rad}

Peak target temperature decreases as f_{rad} increases for both divertor concepts



<u>Lehmer Peak Target Temperature</u>

$$T_{tpeak} = \frac{\int T^{30}\, ds}{\int T^{29} ds}$$

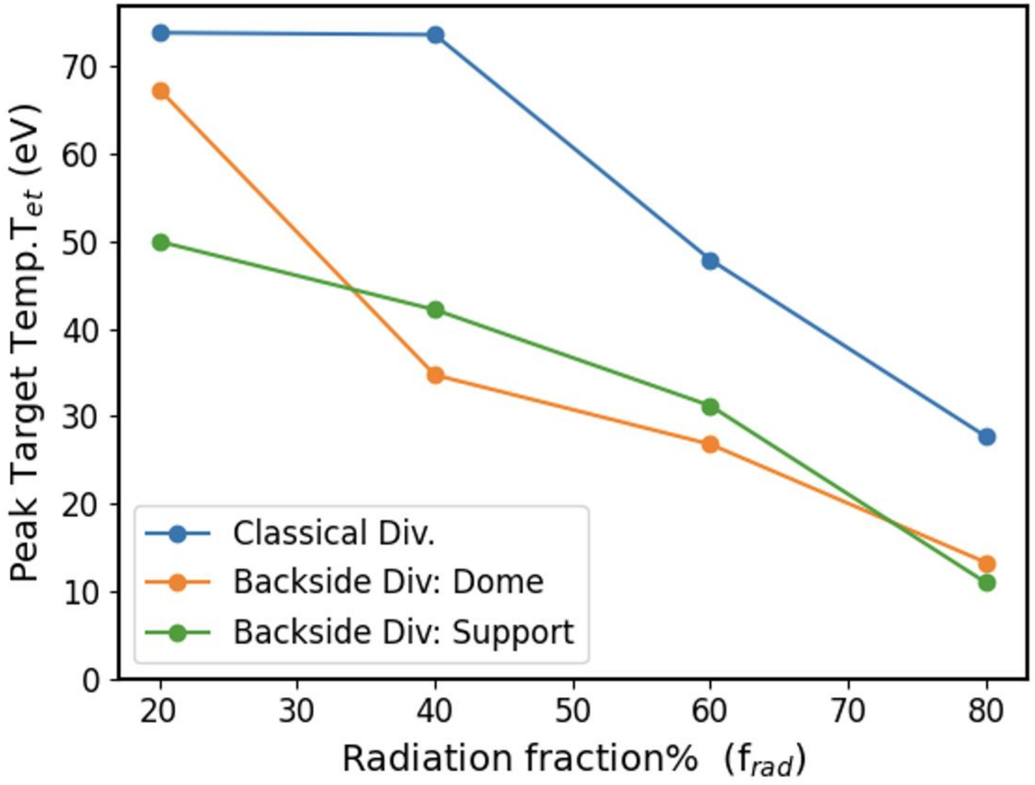
Where T = Target temp. in eV

s = entire surface area of the relevant target

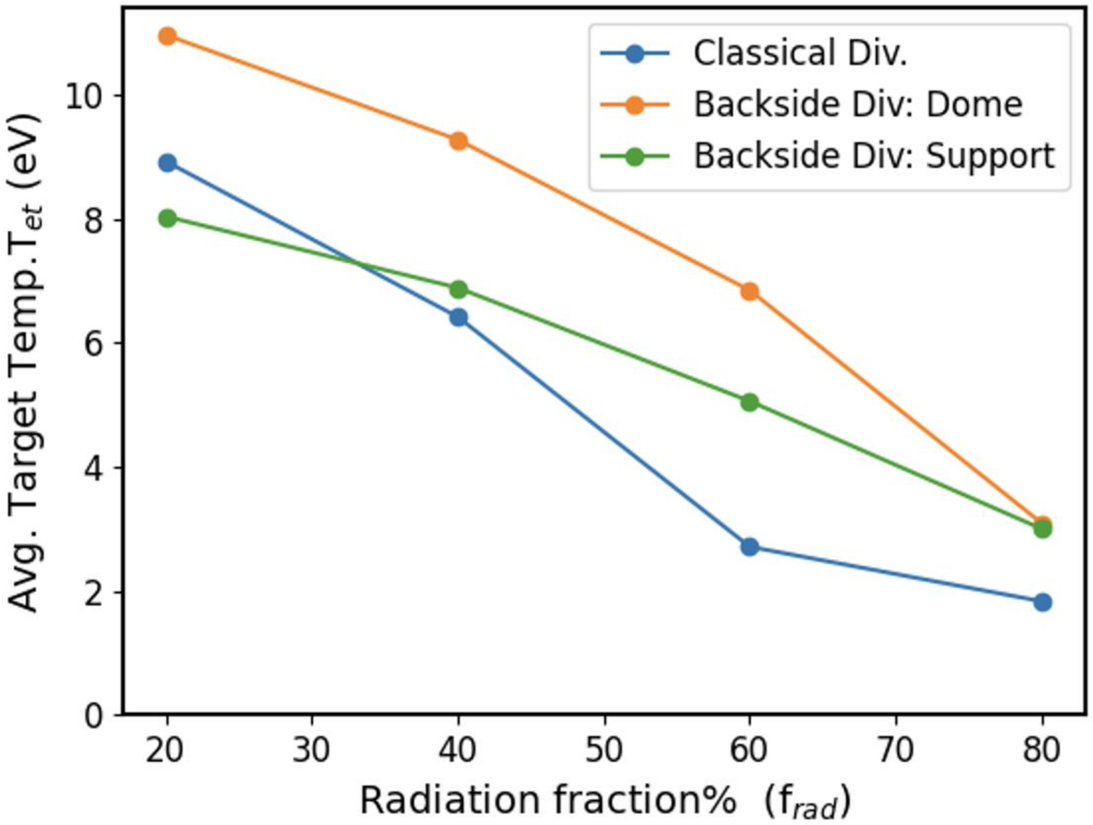
Γ_s= particle flux at the surface element ds

Flux average target temperature decreases as f_{rad} increases for both divertor concepts

Lehmer Peak Target Temperature



Flux Average Target Temperature



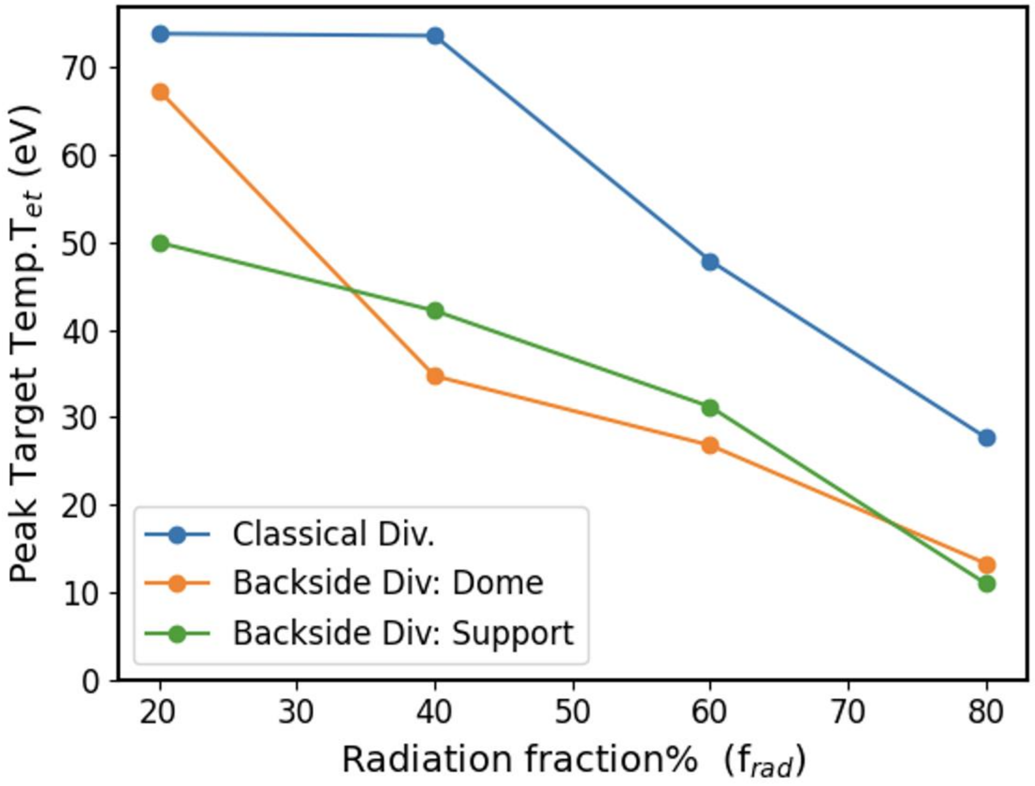
$$T_{tpeak} = \frac{\int T^{30}\, ds}{\int T^{29} ds}$$

➡ f_{rad} > 80 needed to decrease the temp. to engg. limits

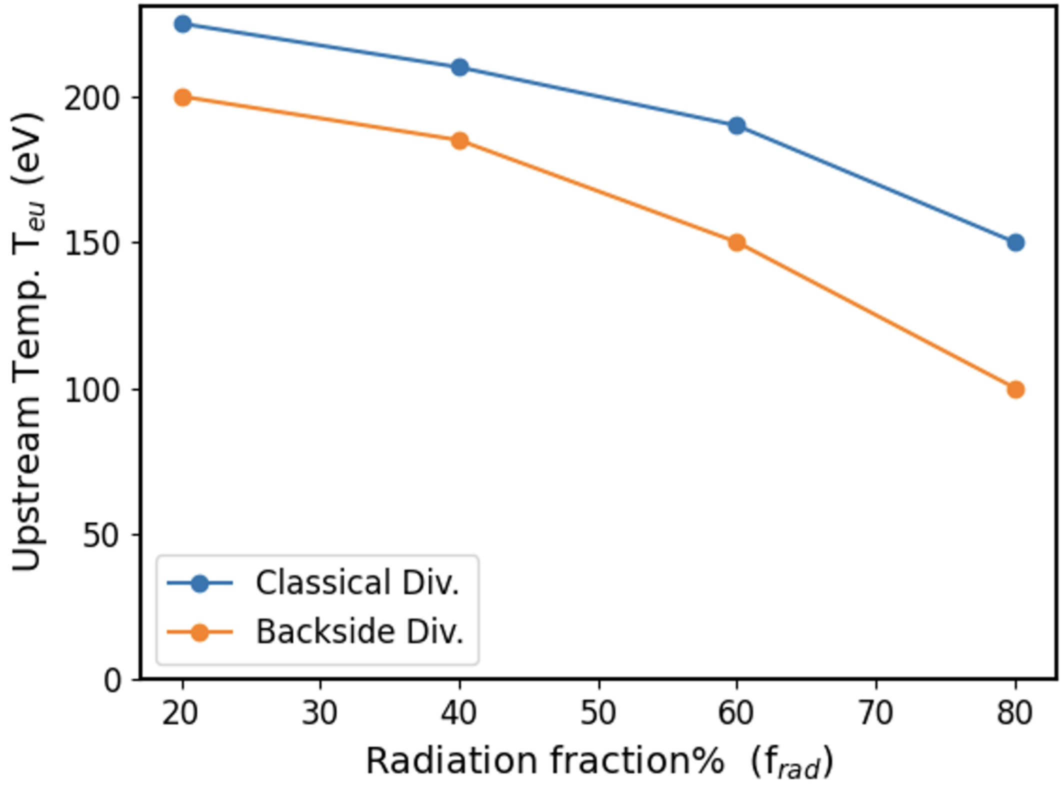
$$T_{tav} = \frac{\int T\, \Gamma_s ds}{\int \Gamma_s ds}$$

Temperature at separatrix is greater than 100 eV at high f_{rad} for both divertor concepts

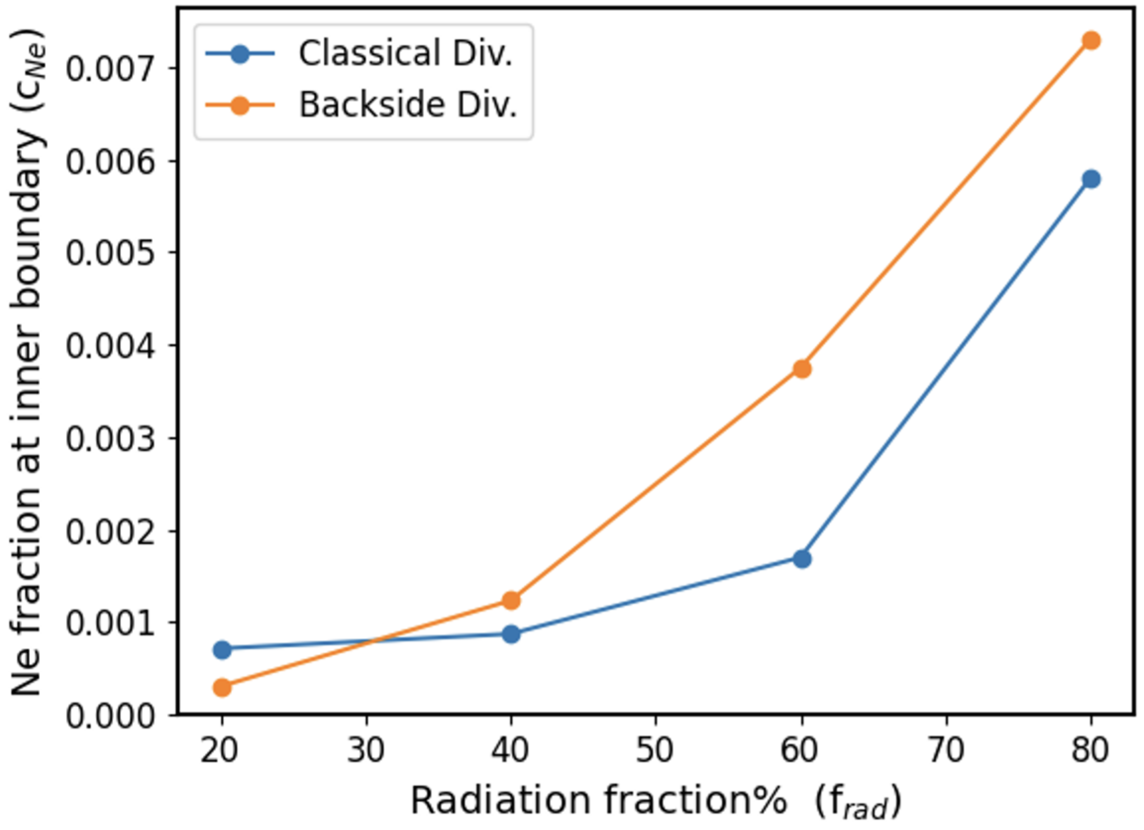
Lehmer Peak Target Temperature



Temperature at Separatrix



Required Neon concentration consistent with plasma core assumptions



<u>Neon fraction at core boundary:</u>

$$c_{Ne} = \frac{n_{Ne}}{n_{plasma}}$$

- Even at high radiative fraction and high upstream density $n_{IBS} = 7 * 10^{13}$ cm^{-3}, concertation of Neon in the core is maintained small

Note: From core modeling, $f_{Ne,lcfs}$= 0.005 give $f_{rad,core}$=40-50%

Ref: Guttenfelder, W., et al. JPP 91.3 (2025): E83

Summary and Discussions

- First of its kind -- 3D plasma-neutral simulations for a reactor scale stellarator power plant!
- Downstream density higher than the upstream density is expected in Infinity Two
- With increasing f_{rad}, target temperature reduces, and sufficiently low heat flux on target is achievable in Infinity Two
- Higher f_{rad} will be required to reduce the target temperature and control the sputtering
- Simulations show Infinity Two retains relatively high T_{lcfs} and manageable levels of $f_{Ne,lcfs}$ at high f_{rad}, as required for core

Ongoing and Future Work

- To demonstrate access to sufficiently small peak target temperature while maintaining sufficiently high LCFS temperature
- To evaluate the neutral pressure on the targets/pumps and correlate it to the plenum pressure to determine pumping speed required
- To understand the stability of detachment at higher f_{rad} (X- vs O- stability)
- To understand the sensitivity of χ, D on detachment and other physical parameters especially heat flux width

Thank you!